CHAPTER 3

ALLOWABLE VIBRATION LEVELS

3-1. General. The usual practice is to adopt a maximum allowable particle velocity as a means to avoid cracking of adjacent building structures. The theoretical basis for this practice is given in Equation (3) where maximum strain is shown to be linearly related to maximum particle velocity under ideal conditions. Most blasting induced damage occurs in brittle materials which crack when a maximum allowable tensile strain or a maximum allowable strain energy are achieved (Item 22). For a given brittle material, maximum allowable strain and maximum allowable particle velocity correlate. From the material presented in Chapter 2, the maximum particle velocity at a given distance from a proposed blast can be estimated from a working curve based on past measurements or from published formulas. Comparisons of the prediction with the allowable value determines whether there is a significant potential for cracking or other building damage at a given range. Rather than adopt a single standard maximum particle velocity value which in some situations would be overly conservative, this chapter will present descriptions of various damage levels and the levels of motion at which they are likely.

3-2. Types of Damage. Damage to buildings can be grouped in three categories (Item 14):

Threshold: Formation of new minor cracks in plaster or at joints in walkboard, opening of old cracks and dislodging loose objects.

Minor: Superficial, not affecting the strength of the structure; for example, loosened or fallen plaster, broken windows, significant cracks in plaster, hairline cracks in masonry.

Major: A significant weakening of the structure, large cracks, shifts of the foundation, permanent movement of bearing walls, settlements which cause distortion of the structure or walls out of plumb.

Threshold damage is always cosmetic in nature as it does not affect the usefulness of the structure but can result in an economic loss. Most minor damage such as cracking of masonry is also cosmetic in nature, but can cause loss of use of the structure until repaired. Most minor damage can be quickly repaired. In general, cracking is more likely to occur in older structures which have already suffered prestraining and fatigue, and in plaster rather than in newer wallboard construction.

3-3. Damage Surveys. Because many other things beside blasting can crack buildings (aging, thermal cycles, foundation settlements, slamming doors, etc.), and because people rarely notice the effect of these events until after someone has blasted in the area, pre-blasting damage surveys are important in reducing claims. If the owners will permit it, off-site pre-blasting property inspection with photographs and records should be made. These inspections are effective in settling damage claims. The use of video cameras is a very effective procedure. Structures can accept vibration levels that occupants find very troublesome. Thus people tend to look at their building very closely after a blast and notice cosmetic damage that was present before the blast but which had not been noticed in more casual examinations. Pre-blast photographs and video records help solve that problem. Pre- and post-blast damage surveys of the interior and exterior of nearby structures are recommended when operating close to a damage threshold or when public concern is strong.

3-4. Data on Residential Structures and Basements. Items 9 and 14-21 present data and analyses of the performance of residential structures subjected to blasting vibrations. The threshold of cracking reported in these studies ranges from 0.8 to 11.8 in./sec. The data show that the higher the frequency of the maximum particle velocity, the higher the threshold. The data also show a trend in which surface mine blasting produces lower thresholds than quarry blasts which are in turn lower than construction blasting. This trend is consistent with the frequency effect as shown by the relation of the predominant frequencies in the three types of events in Figure 4.

Figure 8 shows that when the maximum particle velocity component in any direction exceeds 2.0 in./sec, the threshold of cosmetic damage begins. Minor damage begins at about 5.4 in./sec in the data set shown in the figure and major damage at about 7.6 in./sec. Note the 4 threshold damage points below 2 in./sec (actually at about 3/4 in./sec.) Similarly, a limited number of cases of threshold damage have been noted in older structures in surface mine blasting at particle velocities of 1/2 in./sec (Item 9).

Figure 9 is another data set for blasting near residential areas (Item 15). This figure shows more than 100 observations of no blasting damage to residential structures at particle velocities in the 2-6 in./sec range. These two figures indicate that the damage threshold particle velocity is a random variable and that it is highly improbable but not impossible that the threshold of damage will lie below 2 in./sec. Cases below the 2 in./sec level where no damage occurred are not shown but there are many such cases.

3-5. Various Published Criteria. Criteria for the maximum permissible particle velocities at residences have been recommended for surface mining operation by the Bureau of Mines at 0.75 in./sec for modern residences and 0.5 in./sec for older structures. The Bureau of Mines indicates that one of the motivations for the recommended levels was human irritation with and tolerance of repeated blasting operations (see Paragraph 3-7). The Bureau of Mines has established a 1.0 in./sec criteria for commercial surface mining blasting in the proximity of human habitation. In March 1983 the Office of Surface Mining changed this criteria to permit alternate use of the allowable maximum velocity-frequency chart shown in Figure 10. These criteria do not necessarily apply to construction blasting. Chapter 7 of EM 1110-2-3800, adopted a 2.0 in./sec criteria as did earlier Bureau of Mines documents (Item 21). No specific criteria are established in this document except as

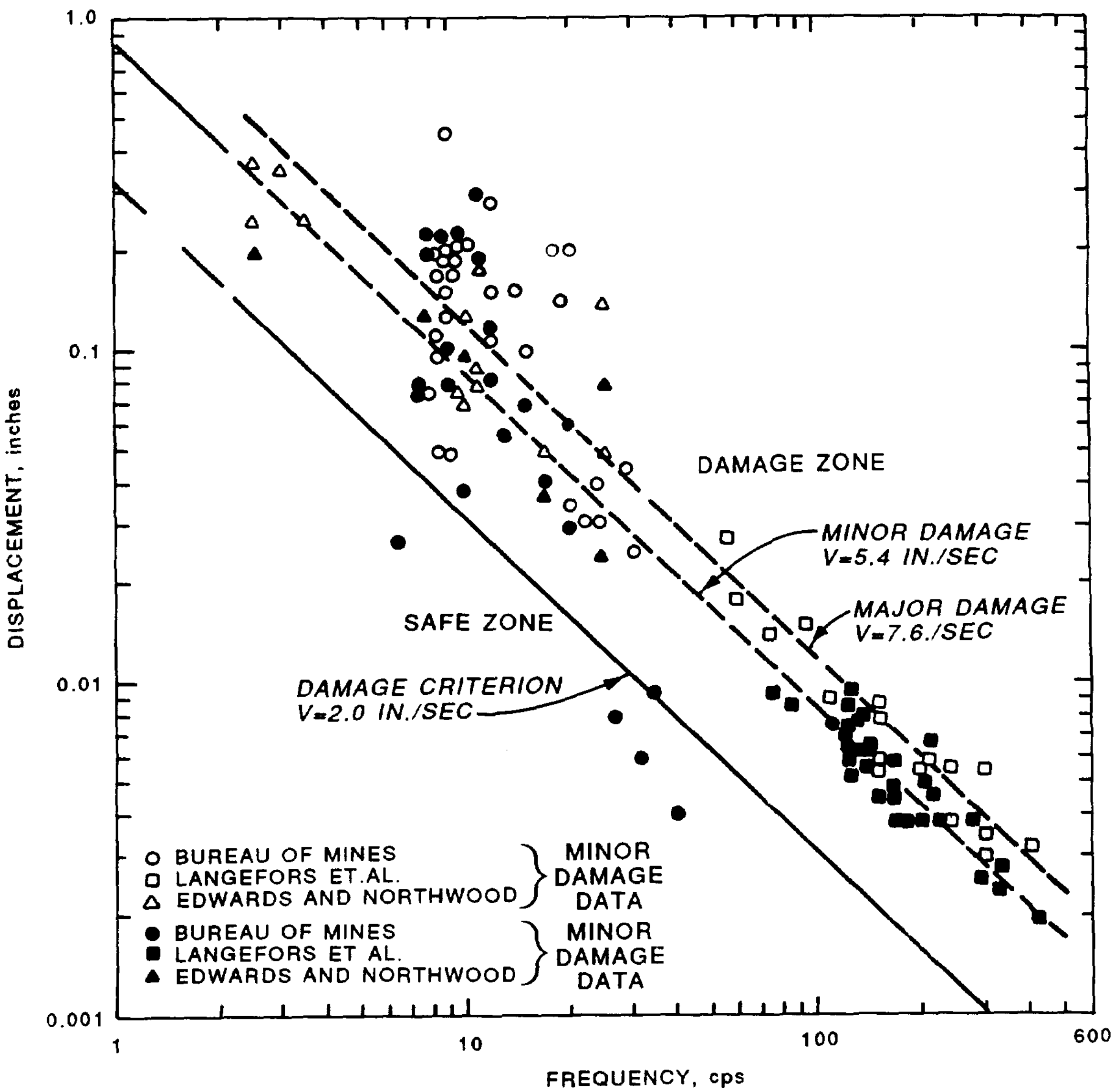


Figure 8. Effect of maximum ground displacement, maximum particle velocity and frequency on damage to residential structures (Item 15)

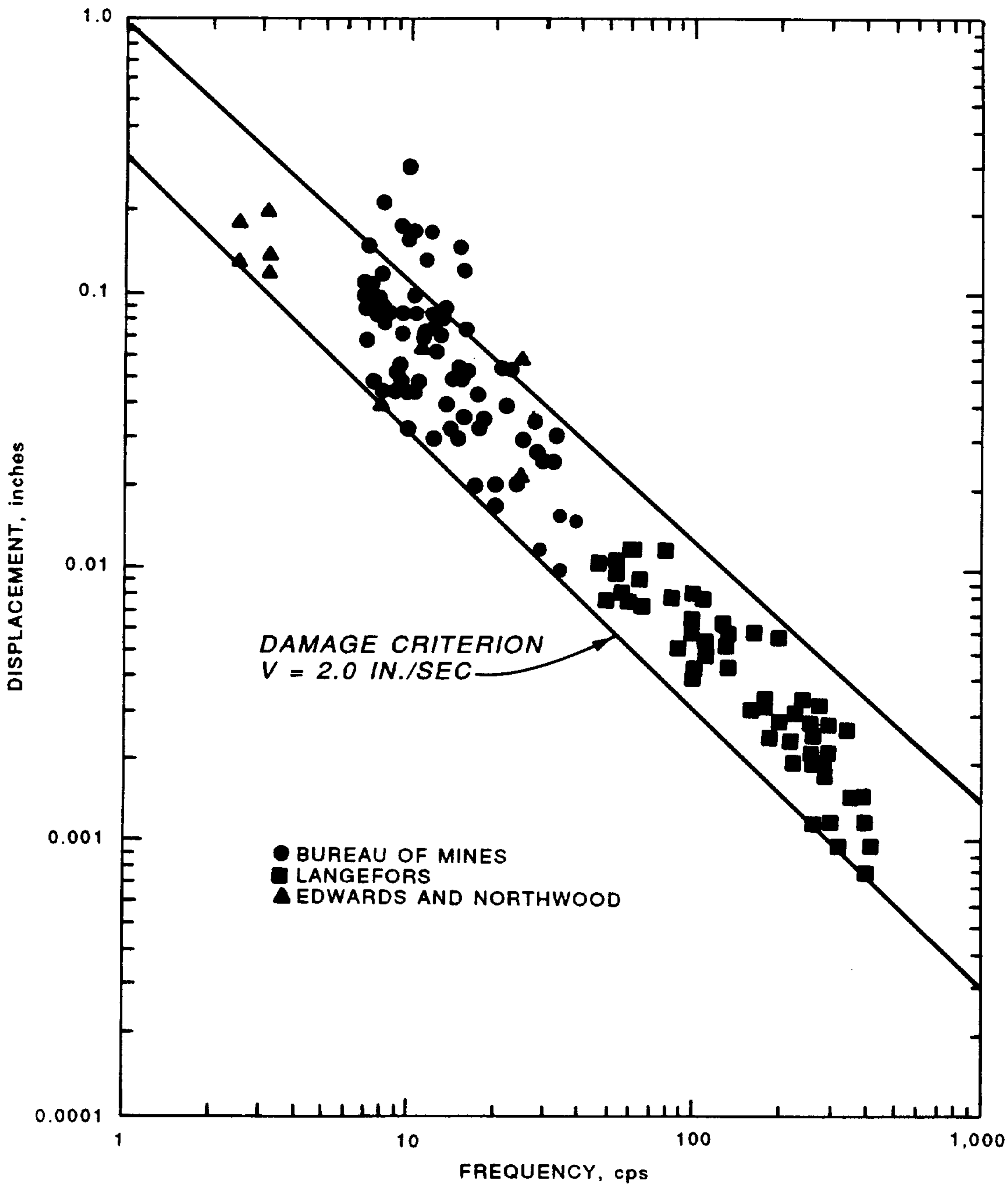


Figure 9. Recorded non damage cases where maximum particle velocity at residential structures exceeded 2 in./sec (Item 15)

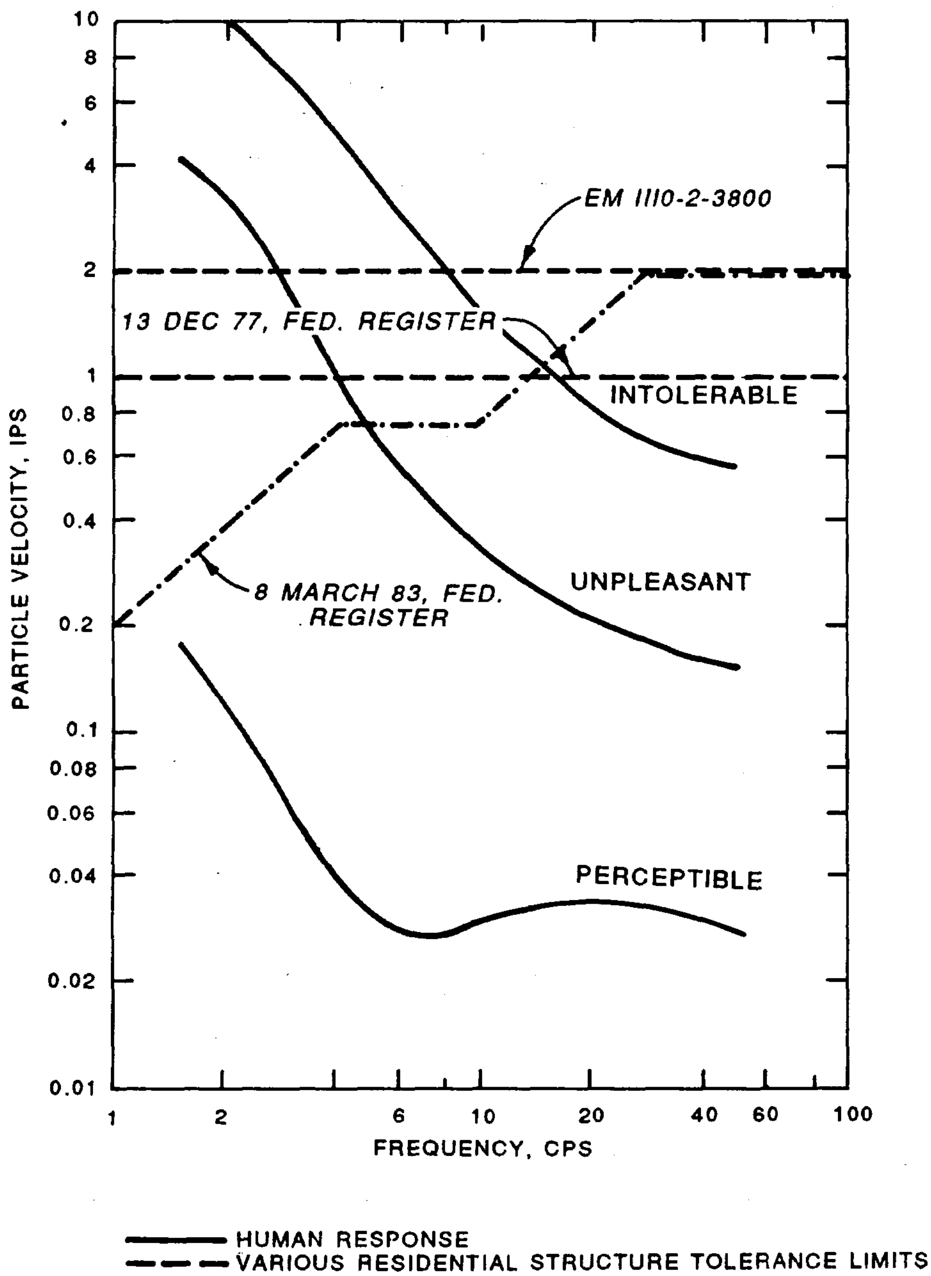


Figure 10. Comparison of human response to steady state vibration as a function of frequency and various blasting vibration criteria for residential structures

already noted. The design engineer or equivalent should consider the age of the structure, the condition of the structure, the type of blasting (construction or quarry) and pick a threshold value consistent with the expected frequency content of the motion and the appropriate level of risk of damage.

3-6. Frequencies. Figure 4 shows that predominant frequencies observed in measurements of constructing blasting range from 10 to 40 Hz while those from quarrying operations are in the 5-30 Hz range. Frequency decreases with range as can be seen from Figure 2. Particular stratigraphic arrangements can enhance particular ground motion frequencies (see Equations (8) and (9)). Likewise, particular structural arrangements of buildings or components when excited by ground vibrations have a natural preference to vibrate at a particular frequency called a natural frequency. Typical natural frequencies are as follows:

Table 3

Typical Natural Frequencies

Structure or Element	Natural Frequency, Hz
Multistory building	f = 0.1N, N = number of stories
Radio tower 100 ft tall	3.8
Petroleum distillation tower 65 ft tall	1.2
Coal silo, 200 ft tall	0.6
Building walls	12-20
Wood frame residences (1 and 2 story)	7.0 Standard deviation = 2.2

Most vibrations from construction blasting and nearly half of the vibrations from quarry operations are at frequencies above the range given above. A residential structure will respond less (that is, strain less) when shaken by a 1 in./sec maximum velocity ground motion at a principal frequency of 80 Hz than it will to a 10 Hz ground motion with the same maximum velocity. The structure tends to resonate (that is, vibrate at ever increasing amplitudes) when shaken by a ground motion with a large number of cycles at or near its natural frequency. While this tendency to increase without limit is controlled by damping and the transient nature (nonsteady state) of the blasting induced ground motion, increases of a factor of 4 in response due to this phenomena are not uncommon. In the absence of velocity versus time data from a test blasting program at the site, from which frequency of ground motion can be determined, it is recommended that construction and quarry blasting peak particle velocities at the nearest residential structure be limited to 2.0 in./sec or less. Experience indicates the probability of damage to residential structures is at or below this level will be very small.

3-7. Human Perception and Tolerance. Figure 10 shows the effect of steady state vibration on individuals, determined from a systematic research program described in Item 23. Blasting vibration is transient and less disturbing. Crandall (Item 20) published curves on human response to transient vibration.

Item 24 reviewed previous works and compared the effects of transient motion with and without accompanying noise and observer bias. A summary of the classification given in that source is presented in the table below.

Table 4

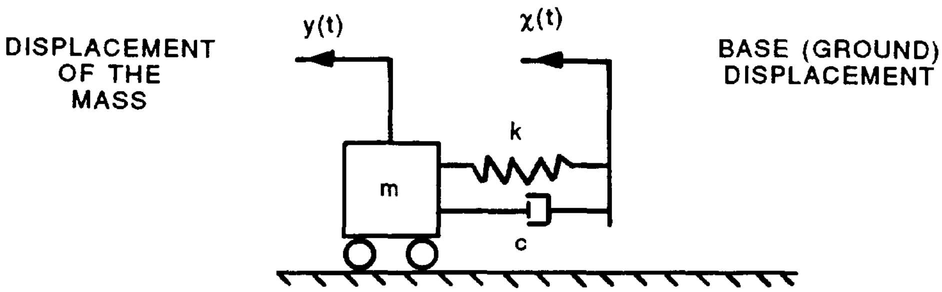
Human Perception of Blasting Effects

Maximum Particle Velocity in./sec	Transient Motion, No Sound Effects, Impartial Observer	Blasting Accompanied by Sound Effects, Biased Observer
0-0.02	"Not noticed"	"Not noticed"
0.02-0.06	"Not noticed"	"Noticed, complaints possible"
0.06-0.20	"Noticed"	"Noticed, complaints possible"
0.20-0.40	"Noticed"	"Severe complaints likely"
0.40-1.20	"Disturbing"	"Severe complaints likely"
1.20-2.00	"Severe"	"Severe complaints likely"

The above table and Figure 10 indicate that humans are less tolerant of low frequency blasting vibrations than are buildings, and that accompanying noise and bias against the project on which the blasting is being done make them more unwilling to accept transient vibration. The previous table indicates that repeated blasting operations with maximum particle velocities of over 1/2 in./sec at occupied structures will produce complaints and that operation at the 1/4 in./sec level may in some cases result in complaints. Good blasting practice includes consideration for these human responses at off-site locations.

3-8. Response Spectra. In the sections of this paragraph which follow, tolerances of some specific structures and materials of interest to CE projects and for which performance data are available will be discussed. In this section, an approach involving the use of the response spectrum to provide input to the structural engineer's estimate of the vibration tolerance of other structures will be presented. The response spectrum is a means of describing to the designer what vibrations are expected and is in a form that can be used directly in a dynamic, structural analysis of linear elastic structures.

If a linear single degree of freedom system (SDFS) consisting of a mass (m), spring (spring constant = k) and viscous damper (damping coefficient = c) is subjected to a base motion [x(t)], the relative response of the mass, with respect to the base at time (t), (y(t) - x(t)), is a measure of the internal force in the system and hence its likelihood of sustaining damage. Figure 11 shows a single degree of freedom system and defines terms used in this section. If the ground motion expected is known as acceleration ($\ddot{x}$) as a



SINGLE DEGREE OF FREEDOM SYSTEM (SDFS)

$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$ = UNDAMPED NATURAL FREQUENCY

$\xi = \frac{c}{2\sqrt{m \cdot k}}$ = % OF CRITICAL DAMPING

$U = \left| \left[y(t) - x(t) \right] \right|_{max}$ = MAXIMUM RELATIVE DISPLACEMENT OF SDFS

$V = 2\pi f U$ = MAXIMUM PSEUDO-VELOCITY OF SDFS

$A = 4\pi^2 f^2 U$ = MAXIMUM PSEUDO-ACCELERATION OF SDFS

$\left[y(t) - x(t) \right] = -\frac{1}{2\pi f} \int_{\tau=0}^{\tau=t} \ddot{x}(\tau) \sin 2\pi f(t-\tau) d\tau$ = RELATIVE DISPLACEMENT OF SDFS AT TIME = t

$x(\tau)$ GROUND ACCELERATION AT TIME = τ

τ = A VARIABLE OF INTEGRATION

Figure 11. Single degree of freedom system and equations relating to the response spectrum for a single degree of freedom system

function of time, the response spectrum for an undamped* ($c = 0$) system can be computed by repeatedly calculating the Duhamel Integral shown in the figure for $\ddot{x}(t)$ for all possible values of t, various values of system natural frequency (f), and determining the maximum relative displacement U at each frequency. It is common to plot the response spectrum on tri-particle logarithmic paper, shown in Figure 12, as pseudo-velocity versus undamped natural frequency (f), where the pseudo-velocity (V) equals:

$$V = 2\pi fU = 2\pi f \left| [y(t) - x(t)] \right|_{max} \qquad (15)$$

Figure 12 illustrates several points that should be understood by the user:

- Lines sloping up to the right at a 1 on 1 slope are lines of constant maximum relative displacement (U).

- Lines sloping down to the right at a -1 on 1 slope are lines of constant pseudo-acceleration (A).

- Tripartite log paper allows the simultaneous expression of A, V and U.

- At very low SDFS frequencies, the maximum relative displacement (U) asymptotes to the maximum ground displacement x_{max}.

- At very high SDFS frequencies, the maximum pseudo-acceleration (A) asymptotes to the maximum ground acceleration $\ddot{x}_{max}$.

- As the percentage of critical damping increases, the maximum relative displacement, pseudo-velocity and pseudo-acceleration decrease.

Figure 12b presents the response spectrum obtained for a point close to a large millisecond delay blast. By comparison to Figure 12a, the amplitude of the spectrum is much larger and the center frequency has shifted to a higher frequency as would be expected since the dispersive nature of earth materials attenuates high frequencies with increasing distance. In the case of a multi delay round, the center frequency of the spectrum is approximately equal to 1/delay interval. Also shown in Figure 12 is a reinterpretation of the data in Item 14 in terms of limiting response spectra for threshold damage to residential structures presented in Item 26. The spectrum for the blast lies under the bounding spectrum and is expected to cause no damage.

Research has shown that if the ground displacement, maximum particle velocity and maximum ground acceleration are known, multiplying factors can be

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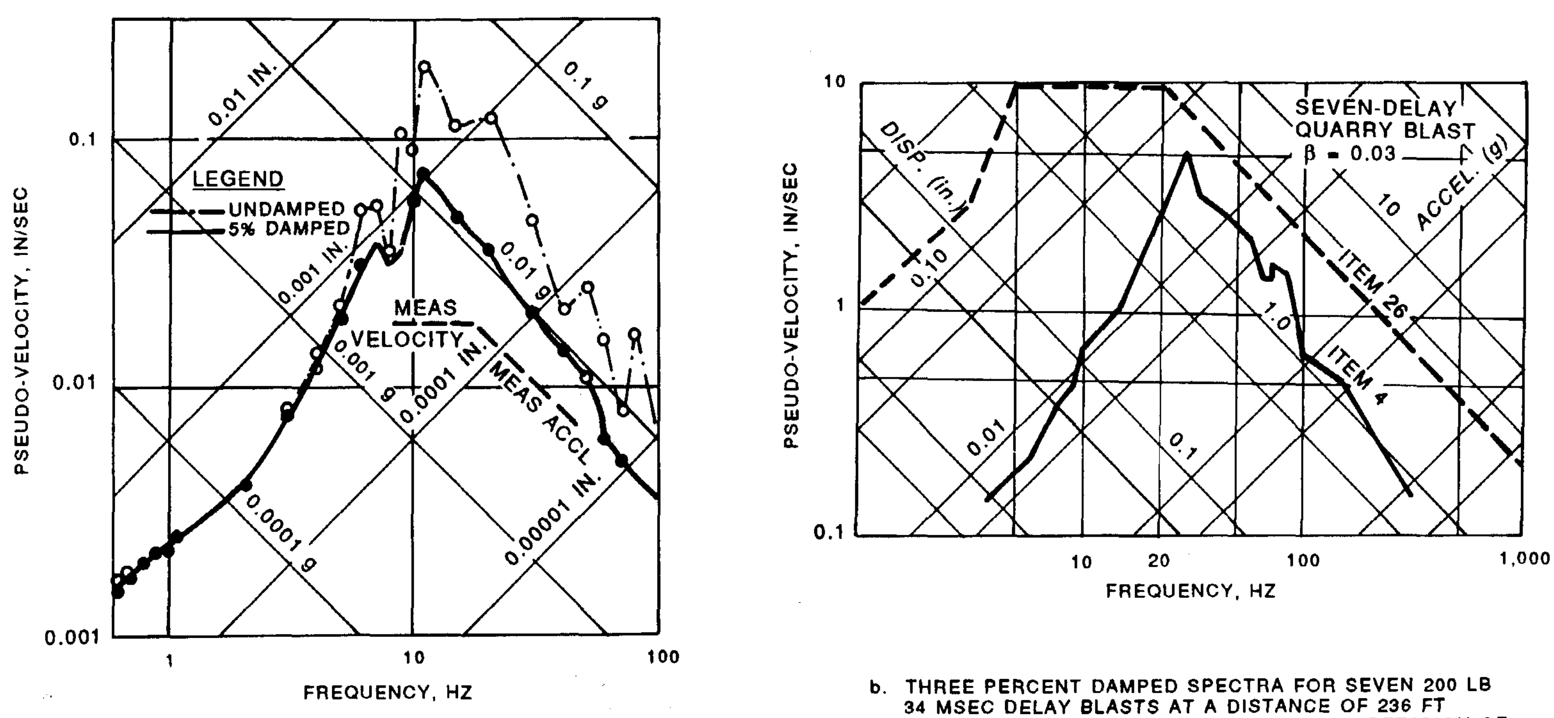
* Similar equations are available for damped systems. See Items 4 and 25. Computer programs to accomplish the calculations are available from CEWES-GH.



a. ZERO AND 5 PERCENT DAMPED SPECTRA FOR RADIAL MOTION CAUSED BY A 100 LB, DETONATION AT R = 2,800 FT (ITEM 6)

b. THREE PERCENT DAMPED SPECTRA FOR SEVEN 200 LB 34 MSEC DELAY BLASTS AT A DISTANCE OF 236 FT (REFERENCE 4) COMPARED TO A REINTERPRETATION OF THE EDWARDS AND NORTHWOOD DAMAGE CRITERIA (ITEM 26)

Figure 12. Example of response spectra for blasting vibrations

applied to produce spectra which will envelope the actual response spectra. Procedures for doing this are given in Items 4 and 5. These enveloping spectra can be given to the structural analyst who can use them as input to dynamic analysis to determine the response of a complex structural system to the blasting vibration and assess the structure's performances.

In Item 4, an equation for maximum ground acceleration $\ddot{x}_{max}$ prediction, is presented. It is as follows:

$$\ddot{x}_{max} = \frac{314}{386} g \times \left(\frac{100 \text{ ft}}{R}\right)^{1.84} \left(\frac{c}{10{,}000 \text{ ft/sec}}\right)^{1.45} \left(\frac{W}{10 \text{ lb}}\right)^{0.28} \left(\frac{4.66}{\rho}\right)^{0.28} \tag{16}$$

where

c = seismic P wave velocity of the rock ft/sec

ρ = mass density of the rock, $\text{lb/sec}^2/\text{ft}^4$

The pseudo-acceleration (A) for the enveloping 3 percent damped response spectrum is

$$A = 2.5 \ddot{x}_{max} \tag{17}$$

Equations for predicting maximum particle velocity $u_{R_{max}}$ are given in Equations (10) through (14). The maximum pseudo-velocity (V) for 3 percent damping can be determined by using the appropriate single delay or multiple delay amplification factor from Figure 13.

The ground displacement (x_{max}) can be estimated for the following equation from Item 4.

$$x_{max} = 0.0028 \text{ in.} \left(\frac{100 \text{ ft}}{R}\right)^{1.1} \left(\frac{10{,}000 \text{ ft/sec}}{c}\right)^{1.4} \left(\frac{W}{10 \text{ lb}}\right)^{0.7} \left(\frac{4.66}{\rho}\right)^{0.7} \tag{18}$$

and the relative displacement bound (U) for 3 percent damping is 1.2 x_{max} for all blasts except rounds which have deep soil cover or are full tunnel rounds, where $U = 2.5 x_{max}$. Conversion to other degrees of damping can be obtained by multiplying the amplification factors in Table 5 (Item 4).

While Paragraph 3-8 presents a lengthy and somewhat mathematically complex procedure, it provides the engineer or geologist concerned with blasting safety with the ability to address, in conjunction with the structural engineer, the safety of structures for which no empirical data base of prior blasting experience exists and a method that rationally treats the different damage potentials of like amplitude motions of different frequencies. For these reasons the method is gaining wide acceptance in practice.

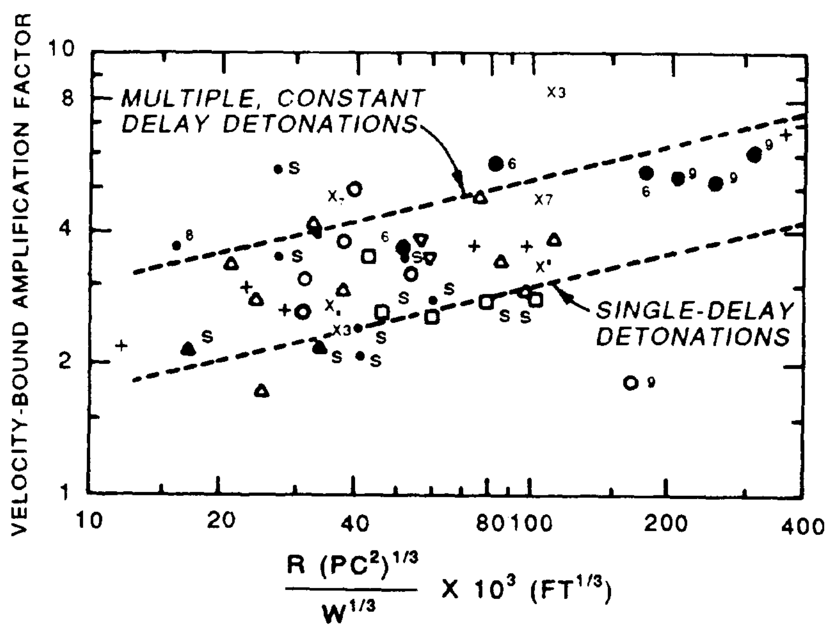


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Figure 13. Pseudo-velocity amplification factors (Item 4)

Table 5

Damping Effects

% Critical Damping	Displacement Bound	Pseudo-Velocity Bound	Pseudo-Acceleration Bound
3	1.0	1.0	1.0
5	0.83	0.76	0.72
10	0.65	0.52	0.42

3-9. Concrete Structures. This paragraph treats the effect of blasting on massive concrete structures such as bridge piers, gravity retaining walls, lock monoliths, concrete gravity dams and tunnel liners. The effects of blasting vibration on reinforced concrete beams, columns and wall structures, if they must be predicted, should be calculated by methods of structural dynamics using the spectra from the preceding section as input. Generally, aged mass concrete withstands blasting vibrations well and the most common blasting vibration questions relate to green concrete.

Concrete is much weaker in tension than compression. The tensile stress waves in the concrete are of primary concern in blasting vibration. In one dimensional wave propagation, the maximum stress is related to the maximum particle velocity

$$\sigma_t = \rho c u \tag{19}$$

where

σ_t = allowable tensile strength (taken as 10 percent of the unconfined compressive strength), lb/sq ft

ρ = mass density = 150 lb/cu ft/32.2 ft/sec^2 = 4.66

c = seismic velocity of concrete taken as 10,000 ft/sec

u = maximum particle velocity ft/sec

The above analysis can be used to show that no cracking should occur in aged concrete under the following conditions

28 Day Unconfined Compressive Strength psi	Maximum Particle Velocity, in./sec
3,000	11
5,000	18

Items 5 and 10 cite cases where no damage occurred to massive aged concrete structures at peak particle velocities of 4 in./sec at the structure for distances from the structure to the explosive greater than 30 ft. There is no indication that this level was close to the maximum allowable level. Item 9 reports cases where the threshold of cracking in basement concrete walls was reached at 10 in./sec particle velocity. The nature of the cracking suggested this was due to bending moment rather than stress wave effects. Item 27 cites data on the effect of blasting vibrations on mass concrete at various ages and indicates satisfactory performance (no cracking) of 10 day old concrete at particle velocities of 20 in./sec. Item 28 describes precision tunnel enlargement blasting inside a lock wall with a few feet of the wall's surface. The following project specific criteria were developed.

Table 6

Effects on Aged Concrete in Precision Tunnel Enlargement

Event	Strain μ, in./in. $\times 10^{-6}$	Particle Velocity (Assuming c = 13,000 ft/sec) in./sec
Spalling of recent grout on free surface	700	100
Spalling of weathered surface skin	1,300	200
Cracks from shot hole to surface	2,400	325
Blow out of mass concrete	3,800	600

Based on all the above data, a maximum particle velocity of 20 in./sec is recommended for blasting criteria for aged concrete.

Fresh (green) concrete is more susceptible to damage than aged concrete. Data in Item 27 indicates that the following criteria will provide protection against cracking.

Table 7

Allowable Particle Velocity for Concrete as a Function of Age

Age	Maximum Particle Velocity, in./sec
0 hrs	4•DF
4 hrs - 1 day	6•DF
1 to 3 days	9•DF
3 to 7 days	12•DF
7 to 10 days	15•DF
>10 days	20•DF

where DF is a distance factor which varies as follows:

Table 8

Distance Factors

DF	Radial Distance from Blast to Concrete
1.0	0-50 ft
0.8	51-150 ft
0.7	151-250 ft
0.6	>250 ft

These criteria, which have been used by TVA for the last several years, contrast to prior common practice of permitting no blasting within 100 ft of green concrete for 7 days (Item 29) but are amply justified by recent data (Item 30).

3-10. Machinery and Electrical Equipment. In some cases, it is necessary to insure that blasting vibration will not interfere with the operation of equipment. Since most operating equipment causes vibration because it is not perfectly mechanically balanced and these operating limits are given in manufacturer's specifications, blasting should be controlled to produce a 3 to 5 percent damped response spectrum that does not exceed the manufacturer's tolerances expressed in similar terms. Additional data on machinery tolerance can be obtained from Items 4, 31, and 32. Machinery tolerances to vibration are usually specified as displacement amplitudes which are a decreasing function of frequency. A good rule of thumb is that one inch per second maximum particle velocity at frequencies associated with construction blasting is clearly in the troublesome range for most machines. A maximum particle velocity of 1/10 in./sec is generally in the safe range for machine operation.

Electrical and electronic equipment usually have manufacturer specified vibration tolerance levels. Item 4 provides tolerance limits for computer disks drives and telephone switch gear. The rule of thumb for the effect of blasting vibrations on operating machinery can be applied in the absence of specific data for a given piece of electronic equipment.

3-11. Unlined Tunnels. Tests described in Item 34 and reanalyzed in Item 5 provide information for safe distances between underground explosions and unlined tunnels in sandstone and granite. The limit of intermittent failure, mostly spall of rock from the tunnel walls, was found to occur at a radial strain level of 0.0004. Using Equation (3) and the seismic velocity of the rock in question, particle velocity limits can be established on a case by case basis. Since the above contains no safety factor, the maximum allowable particle velocity should be reduced at least to 2/3 of the calculated value.

3-12. Pipelines. Item 4 presents some data on blasting near steel pipelines in soil. Fifteen pound charges 13 ft from a 24 in. diameter, 0.3 in. thick steel pipe caused the pipe to remain in the elastic range. This gives evidence that small charges can be used near pipelines. Performance data for cast iron water pipeline in earthquakes (Item 35) indicate less than one break per 100 km of pipe at 3 in./sec peak particle velocity. This can be used as a very conservative criteria for pipelines at long distances for big explosions where surface waves dominate the motion. Where blasting is required near vital pipeline structures or pipelines carrying hazardous material, a test blasting program should be required.

3-13. Basement Walls. Item 4 reviews data from other sources and recommends 3 in./sec as the limiting particle velocity at concrete block basement walls and 10 in./sec as the limiting velocity on solid concrete basement walls.

3-14. Wells. There are sometimes complaints of loss of productivity of water wells due to blasting. Item 33 indicates no loss in capacity due to vibration at the 3 in./sec level. However, the permanent stress release associated with the blasted excavation itself can cause changes in wells within 300 to 400 ft of the excavation.